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Security–orientated Plastic Optical Fiber sensor in modalmetric configuration

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Abstract

The article describes the operation's rule of the fiber optic sensor in the modalmetric configuration. This type of sensor is described by comparatively simple construction, while retaining other features of fiber-optic sensors such as high sensitivity. A modalmetric fiber optic sensor [1], whose scheme is shown in Fig. 1, comprises a multimode sensor fiber, a light source for launching light into the multimode fiber to produce a multimode speckle pattern of light at an end of the fiber, a single mode fiber to receive light from the multimode speckle pattern and a detector connected to the single mode fiber to detect the received a partial light from the multimode speckle pattern. Any disturbance to the fiber which can cause a change in any one of the phase, polarization and distribution of the modes, will cause the speckle pattern to change. By measuring this change, a physical perturbation to the fiber such as a vibration or strain can be detected. This gives a very high potential application. In the paper presents, for example, possible application of the modalmetric sensor to protection of works of art and museum collections. The advantage of its use is the ability to tie the fiber in structure of material. Moreover, the advantage of such type a sensor compared to existing solutions of security sensors is the reaction for vibration and touch. The paper presents the concept and results of the system optimization.

Plastic Optical Fiber sensor; modalmetric fiber sensor;

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1. Modalmetric fiber optic sensor

A modalmetric fiber optic sensor [1], whose scheme is shown in Fig. 1, comprises a multimode sensor fiber (1), a light source (2) for launching light into the multimode fiber to produce a multimode speckle pattern of light at an end of the fiber, a single mode fiber (3) to receive light from the multimode speckle pattern and a (4) detector connected to the single mode fiber to detect the received a partial light from the multimode speckle pattern.

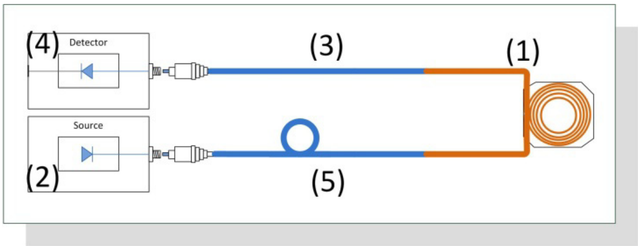

Fig. 1. Arrangement of the modalmetric sensor.

A connector connects the ends of the multimode fiber and single mode fiber with the end faces of the two fibers disposed at an acute single to one another. A modalmetric fiber sensor is based on measuring a change in the speckle pattern output of a multimode (MM) fiber. When coherent light is injected into a standard MM fiber, a large number of modes are excited which will propagate down the fiber. At the output of the fiber, the interference of the modes produces a pattern known as a speckle pattern. Any disturbance to the fiber which can cause a change in any one of the phase, polarization and distribution of the modes, will cause the speckle pattern to change. By measuring this change, a physical perturbation to the fiber such as a vibration or strain can be detected. The modalmetric sensor is therefore a multi-beam interferometer encapsulated within one fiber, where each beam can be represented by one of the propagating modes.

In the multimode fiber propagating modes interact with themselves along their propagation way. This interaction can be observed as stochastically stable intensity distribution at the end-face of the fiber. This distribution can be described in accordance with a Goodman's proposal [2]. Goodman makes some simplifying assumptions to aid in the development of a statistical model for speckle. He assumes that the field incident at (x,y,z) is perfectly polarized and perfectly monochromatic. Under such conditions this field can be represented by a complex-valued analytic signal of the form:

$$u(x,y,z;t) = A(x,y,z)\cdot\exp(i2\pi\nu t) \tag{1}$$

where ν is the optical frequency and A(x,y,z) is the complex phasor amplitude.

The complex amplitude of the field at (x,y,z) may be regarded as resulting from the sum of contributions from many elementary scattering areas on the rough surface. Thus the phasor amplitude of the field can be represented by:

$$A(x,y,z) = \sum_{k=1}^{N} |a_k| \exp(i\phi_k) \tag{2}$$

where $|a_k|$ and ϕ_k represent the amplitude and the phase of the contribution from the k^{th} scattering area and N is the total number of such contributions.

The directly observable quantity is the irradiance at (x,y,z), which is given by:

$$I(x,y,z)=\lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2}\left|u(x,y,z;t)\right|^2 dt=\left|A(x,y,z)\right|^2 \tag{3}$$

In a multimode fiber the light travels in several separate propagating modes, what leads to the consequence that the modes arrive to a receiver separately in time. If the optical radiation is coherent and the coherence time is shorter than the difference in the arrival time of the propagating modes there will appear an interference pattern often called a speckle (3). There is a need to introduce a contrast – quantity that describes discrimination of speckle intensity and can be defined as:

$$V=\frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}} \tag{4}$$

where I_{max} and I_{min} are the maximum and minimum intensity value. The speckle pattern with good contrast is more likely to reveal information than the speckle with the poor contrast. The contrast is a function of radiation source parameters (spectral radiation bandwidth Δf_s, mode spacing Δf_m, modal halfwidth δf) (Fig.1) and the fibre parameters (mode dispersion D_m, fibre length L).

The transmission length of the system will depend on the relationship between laser and the optical fiber. The time delay Δt between modes determines the correlation bandwidth Δf_c of the multimode fiber by a formula [3]:

$$\Delta f_c=\frac{1}{\Delta t} \tag{5}$$

Two interference patterns correlate if the bandwidth of the laser source is smaller than Δf_c. This indicates that if the transmission length is long enough, the time delay will be long and the correlation bandwidth will be poor, so the corresponding contrast of the overall speckle pattern is decreasing (Fig.2) [4]. On the other hand, a laser with a narrow bandwidth results in the speckle with the high contrast.

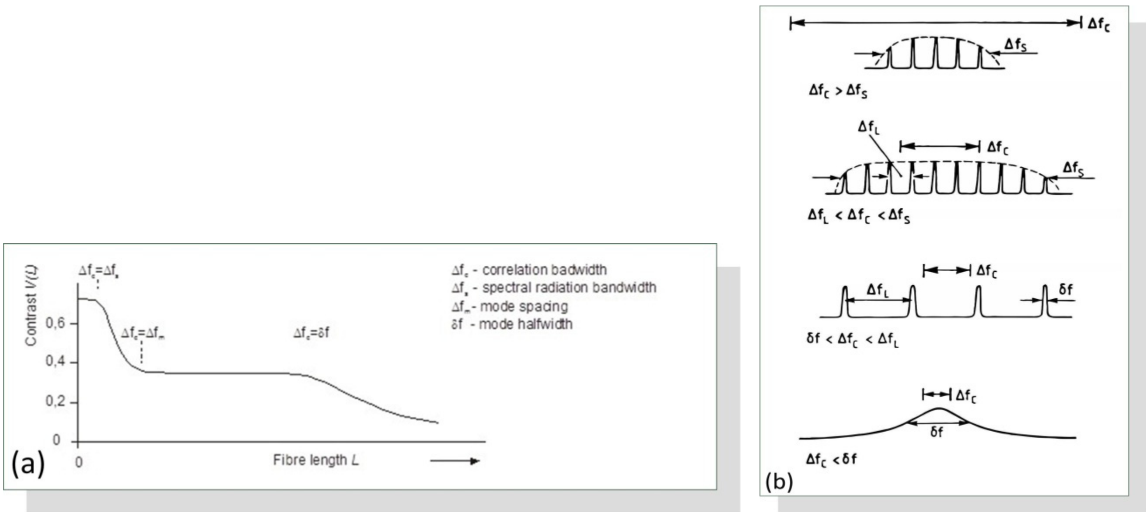

Fig 2. The speckle pattern contrast as a function of the multimode fiber length and the source parameters (a) and its connections with the laser spectrum (b) [4]

There are many factors that influence on the contrast of the interference pattern: transmission length, correlation bandwidth, spectral radiation bandwidth, mode spacing and mode halfwidth [4]. In order to achieve high contrast for the length of the sensor, parameters of the source and the fiber optic should be properly selected taking into consideration the guidelines: number of the laser lines should be small, the laser linewidth should be narrow and the correlation bandwidth of the fiber optic should be high. Laboratory tests that summarize all aspects of the sensor configuration allowed for the optimization of sensor protection.

The detection of a perturbation using the modalmetric effect usually involves detecting a change in the speckle pattern by sampling or interrogating only part of the overall speckle pattern. This can be done through the use of a physical restricting means where only part of the speckle pattern is detected, or through the use of a detector to electronically sample the required area or speckle pattern sub-zone. For this configuration, the speckle detection limit field is single-mode optic fiber (SM) which is placed before the detector. Then, any change in or redistribution of the speckle pattern will be detected as a change in intensity. Since the SM fiber supports only a single mode, it can also act as the insensitive lead-in of the sensing system.

The source radiation, converted into a multimode fiber section, undergoes further transformation on the fiber structure of the intensity distribution defined by the modal distribution described by characteristics of modal structure. Because as a receiver we consider the efficiency of single-mode fiber, which is before the detector, so input to this structure expressed by the relation:

$$\eta = \frac{2\sqrt{2}}{aw_0}\left\{\frac{w}{VJ_1(u)}\int_0^a J_0\left(u\frac{r}{a}\right)\exp\left[-\left(\frac{r}{w_0}\right)^2\right]rdr + \frac{u}{VK_1(w)}\int_a^\infty K_0\left(w\frac{r}{a}\right)\exp\left[-\left(\frac{r}{w_0}\right)^2\right]rdr\right\} \tag{6}$$

As can be seen, the efficiency of introducing of radiation to the structure of the fiber (fiber core) depends on half the diameter necking beam radiation and the fiber core radius a. This parameter lets specify the maximum length of a transceiver single-mode fiber. Of course, the primary impact has the type, spectrum and power of radiation source.

2. Experimental setup

The scheme of the developed modalmetric sensors is shown in Fig. 3. These sensors were elaborated with the use of plastic optical fiber, radiation source of 650nm. Instead of single mode multimode and again single mode fiber we used one piece of POF with two narrowness (I and II in Fig. 3).

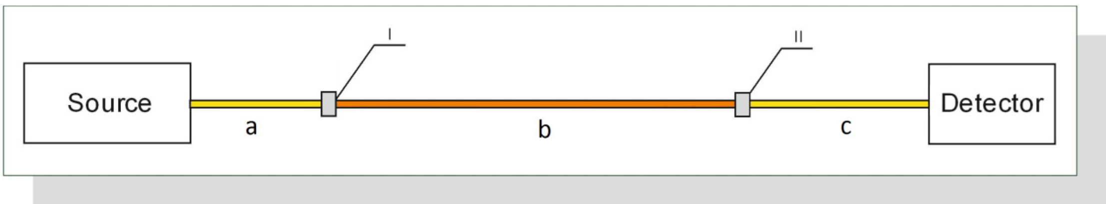

Fig 3. The experimental setup with modalmetric sensor.

The sensor head (“b” part of POF) generates modal interference signal which is transmitted to the measuring and control devices through “a” and “c” part of POF. As the sensor output used standard telephone diode connected to an oscilloscope (type DLM 2054 –Yokogawa) to record the amplitude changes proportional to the intensity changes.

3. Experimental details

With the use of elaborated sensor in modalmetric configuration, the response for numerous disruption of given characteristic was measured. Experimental investigation gave a series of recorded spectra.

First, the study began with record intensity distribution of light level in (according to Fig. 3) I, II and in the end of fiber for different states of sensor: (a) stedy or (b) disturbed. Figure 4, 5, 6 show images of optical radiation recorded at this characteristic cross sections (I, II and in the end of fiber).

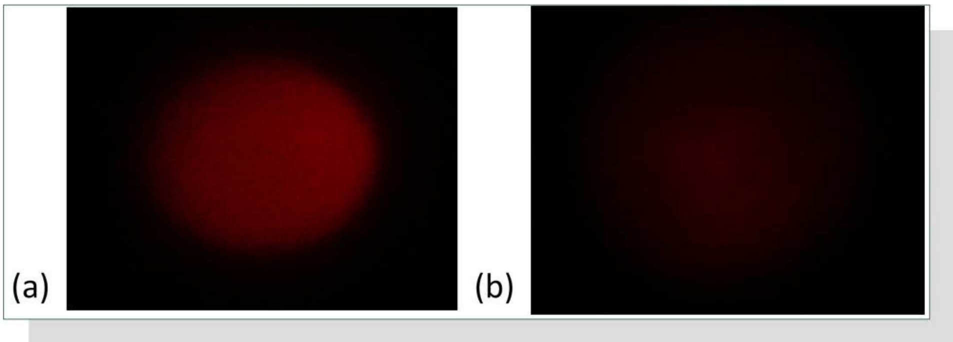

Fig 4. Intensity distributions at I (according to Fig. 3) for different states of sensor: (a) steady or (b) disordered

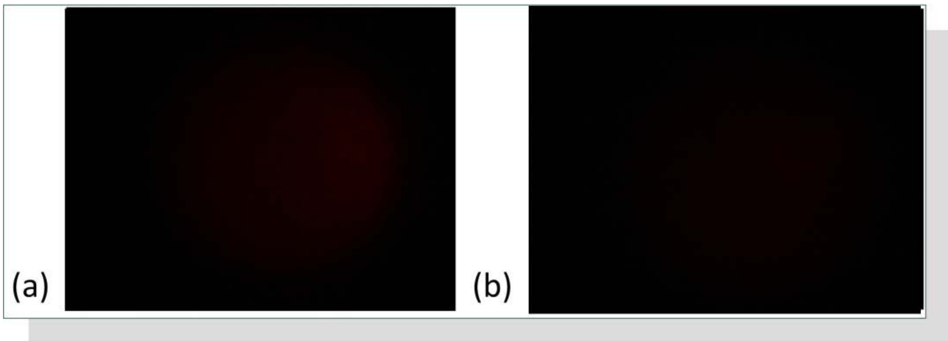

Fig 5. Intensity distributions at II (according to Fig. 3) for different states of sensor: (a) steady or (b) disordered

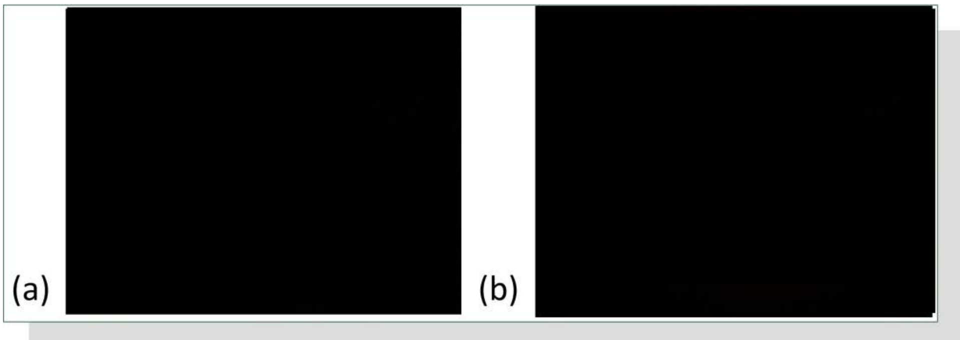

Fig 6. Intensity distributions at the end (according to Fig. 3) for different states of sensor: (a) steady or (b) disordered

The next research step was registration response oscillograms of the system with different level of I and II narrowness. In Fig 7, 8, 9 are presented oscillograms for disturbed sensor for light narrowness, middle narrowness and large narrowness.

Fig 7. Oscillograms system response to hand disorder for light narrowness

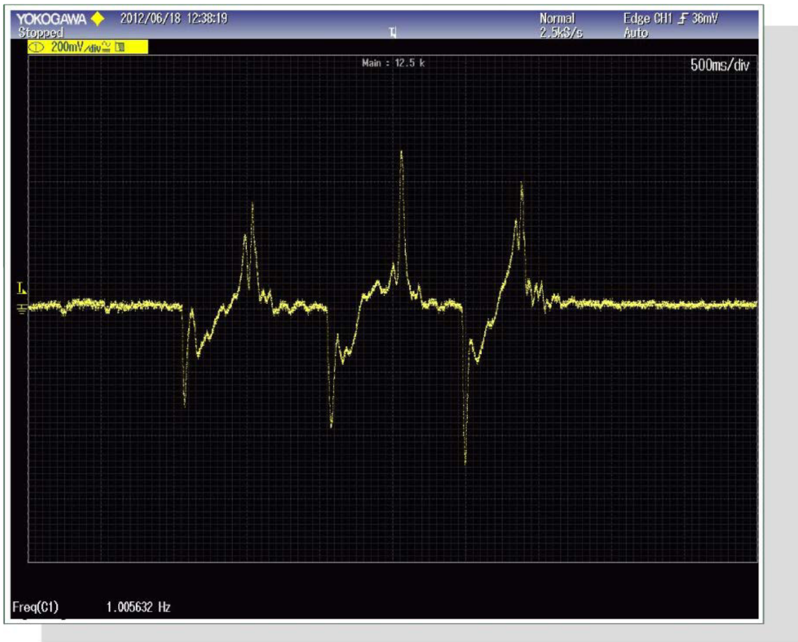

Fig 8. Oscillograms system response to hand disorder for middle narrowness

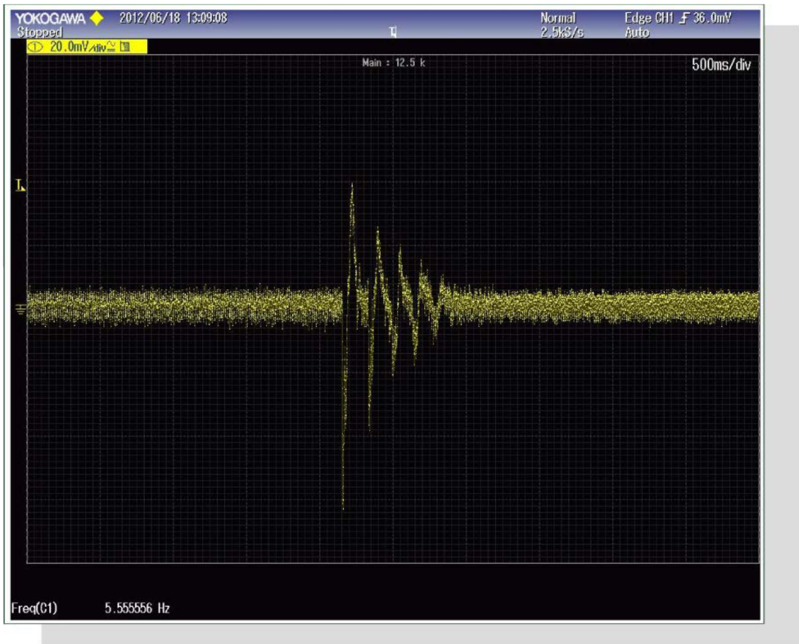

Fig 9. Oscillograms system response to hand disorder for large narrowness

4. Motivation and results

All studies and tests show that it is possible to develop a fiber optic sensor system of simple design with using the basic telecommunications elements. The sensor is sensitive to mechanical disturbances, vibrations and breaking. It will not have an ideal frequency response, but as the sensor will indicate an alarm any attempt to access the transmission medium. [1-9] Authors point to the possibility of using plastic optical fibers for the construction of the sensor. It is a solution that was not so far considered. The paper will present the research and test results of the sensor.

Therefore, we propose to use it for example to protect objects. Where required are: small size sensor, its discreet and effective detection of try to steal.

Acknowledgements

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